# Inconsistencies in Constituent Theories of World Views : Quantum Mechanical Examples*

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**Abstract**

We put forward the hypothesis that there exist three basic attitudes towards inconsistencies within world views: (1) The inconsistency is tolerated temporarily and is viewed as an expression of a temporary lack of knowledge due to an incomplete or wrong theory. The resolution of the inconsistency is believed to be inherent to the improvement of the theory. This improvement ultimately resolves the contradiction and therefore we call this attitude the 'regularising' attitude; (2) The inconsistency is tolerated and both contradicting elements in the theory are retained. This attitude integrates the inconsistency and leads to a paraconsistent calculus; therefore we will call it the paraconsistent attitude. (3) In the third attitude, both elements of inconsistency are considered to be false and the 'real situation' is considered something different that can not be described by the theory constructively. This indicates the incompleteness of the theory, and leads us to a paracomplete calculus; therefore we call it the paracomplete attitude. We illustrate these three attitudes by means of two 'paradoxical' situations in quantum mechanics, the wave-particle duality and the situation of non locality.

## 1 Introduction

If we reflect on the way in which world views are constructed (Apostel and Van der Veken 1991, Aerts, Apostel et al., 1994 a, b, Aerts, Van Belle and Van der

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Veken 1998) we are tempted to think that it is necessary to work towards a 'consistent' view about reality in order to obtain a global perspective on the world. Indeed, in (Apostel and Van der Veken 1991 and Aerts, Apostel et al., 1994 b) the following description of a world view is put forward: 'A world view is a coherent collection of concepts and theorems that allow us to construct a global image of the world, and in this way to understand as many elements of our experience as possible'. The part of this sentence that we want to emphasise is 'coherent collection of concepts and theorems' and we remark that 'coherence' is in principle not equivalent to 'consistency'. Indeed, as we will see, inconsistencies appear in the process of the formation of world views. In this article we will show that there are three main attitudes towards the appearance of inconsistencies, and we will illustrate these attitudes with examples from quantum mechanics.

## 2 Regularising, paraconsistent and paracomplete attitudes

Inconsistencies have appeared in quantum mechanics within a mathematically well defined framework and that is the reason that we can point out the three attitudes we want to distinguish in a detailed way. Our hypothesis is, however, that our classification is more general and applies to inconsistencies within world views in general. The three attitudes that we want to distinguish are the following:

*i) The regularising attitude*

Within the regularising attitude, the inconsistency is understood as a temporary situation of which one of the two contradictory parts will be found wrong and hence eliminated due to new theoretical and experimental findings. The resolution of the inconsistency is believed to be inherent to the improvement of the theory. This improvement ultimately resolves the contradiction. We will see that in the case of quantum mechanics this regularising attitude is usually referred to as a 'classical' attitude. One wants to keep hold of the requirement of consistency and eliminate the inconsistencies: quantum mechanics has known many of these attempts.

*ii) The paraconsistent attitude*

Within the paraconsistent attitude, the inconsistency is accepted as being part of the model, and both contradictory elements are used in a clever manner depending on the situation and need within the model. This view is commonly held by most experimenters and experimentally oriented theoreticians in relation with the inconsistencies of quantum mechanics. In this way, 'old' - but still contradictory - visualisations can be retained. This view allows new experiments to develop in a imaginative way.

*iii) The paracomplete attitude*

Within the paracomplete attitude, the inconsistency is interpreted as pointing out a fundamental incompleteness of the model and none of the two contradicting parts are accepted to be true. The search is directed towards a completion of the model. Most contemporary theoretical interpretations of quantum mechanics follow this line of reasoning; the price of giving up completeness is outweighted by retaining consistency. In practice, although the incompleteness of a theory is only virtual, the gap is immediately closed by introducing a new concept embracing the previously contradictory concepts. This means that old classical images are being replaced by abstract conceptions purely obtained from quantum mechanics, or by new images that do not necessarily have a counterpart in classical physics.

## 3 Inconsistencies within quantum mechanics

Until the end of the 19th century classical physics, Newton's theory of mechanics and Maxwell's theory of electromagnetism, explained very well most of the physical phenomenon of the macroscopic world. Except for the seemingly marginal phenomenon of energy distribution in the radiation of a black body, the science of the physical realm seemed nearing its goal of ultimate truth. But at the turn of the century, the phenomenon of black body radiation became more important. Neither the classical description by Wien's thermodynamically inspired law, nor Rayleigh-Jeans law from electromagnetic vibrations, were able to explain the full range of the spectrum of blackbody radiation as it was experimentally recorded. The introduction of an undividable quantum of action in Planck's description of the black body radiation was, from the point of view of the classical paradigm, completely unexpected. The discrepancy between the classical description of radiation and the experimentally measured radiation of black bodies was solved at the price of giving up the classical principle of continuity of energy. Among the first major classical concepts to fall, the continuity of energy is in hindsight probably the least dramatic one. The shift of the classical to the contemporary quantum paradigm indeed comprises more fundamental conceptual changes, for instance the nature of an entity, states of non-locality, 'quantum' probabilities related to limits of relative frequencies of outcomes, the dual wave-particle aspect of a quantum entity, intrinsic Heisenberg uncertainty relations for non-commuting observables.

These changes are experienced as inconsistencies relative to the classical paradigm. To a certain degree, the historical evolution of the theory gave us ample time to familiarise ourselves with the strange phenomena that appeared. Gradually an integration -albeit only in the scientific community - of these peculiarities took place moving away from the classical paradigm. The emerging quantum mechanical paradigm successfully produced a chain of experiments and descriptions; Einstein's explanation of the photoelectric effect (1905), the Bohr theory of the hydrogen atom (1913), the Bohr-Sommerfeld theory of the atom (1916) and the work of Louis de Broglie on the undulatory aspect of matter. These developments provided the necessary elements to construct a generalised formalism for microscopic systems: the Sommerfeld-Wilson-Ishiwara quantization rules[1]. Still, this first version of quantum mechanics was not flawless; it showed discrepancies with data from experiments on the quantization of the angular momentum. The Sommerfeld-Landé description of an intrinsic magnetic core diminished these discrepancies, and soon were somehow experimentally observed by Stern and Gerlach (1921). The problem was solved when the Pauli exclusion principle inspired Goudsmit and Uhlenbeck to experimentally discover the intrinsic spin of the electron (1925).

Around 1927, the theory of quantum physics was gradually settled. It rested on different proto-theoretic elements such as the matrix approach of Heisenberg, de Broglie's matter waves, and the wave-equation of Schrödinger. Together with the correspondence principle and the complementarity principle of Bohr, quantum theory seemed for the first time grounded in a mathematical consistent theory. At the time the mathematical formalism was finished, there was agreement about the mathematical part but not - and still not - about its interpretation. The theory of quantum mechanics radically transformed the classical scientific paradigm. So, in spite of the operational success of quantum mechanics the inconsistencies with the classical paradigm cause an unanimous interpretation of the fundamental concepts of the theory to remain an unsolved problem. Interpreting quantum mechanics requires concepts that reach way beyond the 'household' concepts of the classical Newton-Maxwell paradigm, to such an extent that the interpretation of quantum mechanics has become a domain of research on its own.

The inconsistencies within quantum mechanics are not inconsistencies of the mathematical formalism, but of the interpretation of this mathematical formalism. In the most general way, it can be stated that for quantum mechanics, 'old classical pictures' that served very well for the interpretation of certain parts of the model described by classical physics, fail to interpret quantum mechanics without leading to paradoxical situations. In this paper we cannot treat all paradoxical situations that appear in quantum mechanics, and therefore we shall limit ourselves to two examples that we shall analyse in detail. In both examples we will point out the three different attitudes that we have put forward.

Our first example is the old and well known quantum mechanical problem of the 'wave' and 'particle' images, and our second example will concern the recently experimentally verified quantum effect of non-locality.

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[1] A good overview of the successes and failures of the Sommerfeld-Wilson-Ishiwara quantization rules can be found in Galindo and Pascual (1990).

# 4 Wave-particle duality

Newton considered light as a collection of particles, that for example were reflected by collision when hitting a mirror. During the first half of the 19th century, the wavelike nature of light was demonstrated by means of experiments entailing the well known wave properties such as interference and diffraction. This made it possible for Maxwell and Fresnel to integrate optics into the field of electromagnetics and consider light as electromagnetic waves of specific frequencies. Light joined the array of other electromagnetic waves, such as radio waves, micro waves, x rays and gamma rays, which differ from each other only in frequency. In this sense the velocity of light, indicated in physics by the symbol $c$, is related to electric and magnetic constants, and the polarisation phenomenon of light is interpreted as a manifestation of the vector character of the electromagnetic field.

As we have mentioned already, the study of the radiation of a black body, which could not be explained by electromagnetic theory, made Planck introduce the hypothesis of the 'quantification of energy' (1900): for an electromagnetic wave of frequency $\nu$, the only energies that are allowed are those which are whole multiples of the 'quantum' $h\nu$, where $h$ is a new fundamental constant. It was Einstein who took Planck's hypothesis seriously and this meant a return to the corpuscular nature of light; light is again considered as a collection of 'photons' of which each of them carries an energy $h\nu$ (1905). Einstein showed how the introduction of the photon made it possible to explain in a very simple way certain characteristics of the photoelectric effect, that had not been explained so far. One had to wait however 20 years more before the photon was directly observed as an individualized particle, by means of the Compton effect (1924)[2]. These results lead to the following conclusion: the interaction of an electromagnetic wave with matter takes place by means of an undivisable elementary process, where the radiation appears as constituted of particles called photons. The typical physical particle parameters, the energy $E$, and the momentum $p$ of a photon, and the typical physical wave parameters, the pulsation $\omega = 2\pi\nu$, and the wave vector $k$, are related by the following fundamental equations:

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\begin{aligned}
E &= \hbar\omega && (1) \\
p &= \hbar k && (2)
\end{aligned}
$$

where $\hbar = \frac{h}{2\pi}$ is defined from Planck's constant $h \approx 6.6210^{-34}$ Joule·second. In the course of each elementary process, there is conservation of the total amount of energy and momentum, as in the classical well known behavior of material particles. These results made a very strong case for the corpuscular nature of light. But did this mean that the wave nature of light was proven to be wrong? Certainly not. If we analyse certain typical experiments, it can be shown that

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[2] Electrons exposed to radiation behave as if they are rebounding from collisions with particles of light.

they cannot be explained by the corpuscular nature of light. One of the well known experiments is the double slit experiment that we will present shortly.

The double slit experiment was proposed much earlier by Thomas Young around 1803 in relation to the investigation of interference effects. At that time this experiment was one of the experiments showing the wave-character of light. At the turn of the century, when the hypothesis of the discontinuity of energy was put forward, the experiment was considered again. As we will show in the following analysis, neither the wave nor the particle picture alone can explain it.

The experiment is performed, using a monochromatic light source, i.e. a source consisting of light of exactly one frequency. As is shown in Figure 1, the source $M$ emits the light that falls upon a screen with two narrow slits, $F_1$ and $F_2$. The light that passes through the two slits is captured on a photographic plate $N$. If one obstructs one of the two slits, for example slit $F_2$, one gets a distribution of intensity $I_1(x)$ on $N$, that is nothing else than the diffraction spot of $F_1$. In the same way, if the slit $F_1$ is closed, the diffraction spot of $F_2$ is described by the intensity distribution $I_2(x)$ (see Figure 1). If the two slits are left open we observe on the photographic plate an interference pattern. One remarks in particular that the intensity distribution $I(x)$ in this case, is not equal to the sum of the two separate intensity distributions $I_1(x)$ and $I_2(x)$.

$$I(x) \neq I_1(x) + I_2(x) \tag{3}$$

Is it possible to explain this result by means of a corpuscular theory of light? The appearance of the diffraction spot for the case where only one of the slits is open, could eventually be explained by the complicated shocks that the photons may receive hitting the borders of the slits. Such an analysis should of course be made in a very detailed way, and then it would turn out that even this effect of diffraction cannot be well explained by considering the light as a collection of particles. For the case of the interference situation where both slits are open we can see the impossibility of a particle explanation more easily. Here we could attempt to explain the appearance of the interference pattern by introducing a possible interaction between photons that pass through different slits. If this were a plausible explanation, the interference pattern should however slowly disappear if we lower the intensity of the source, and disappear completely when the intensity is so low that the photons pass one by one through one of the slits. The experiment shows however that if we lower the intensity of the source such that the photons pass through the slits practically one by one, the interference pattern remains unchanged. This means that even one single photon behaves like a wave in this experiment. Physicists have dubbed this effect 'self-interference'.

Let us now show that the appearance of the interference pattern is perfectly explainable when we consider the wave nature of light. Within the wave description of the electromagnetic field the intensity at a certain point is proportional to the square of the magnitude of the electric field at that point. If $E_1(x)$ and $E_2(x)$ represent, as complex numbers, the electric fields in point $x$ through the slits $F_1$ and $F_2$, the total electric field $E(x)$ in point $x$ if the two slits are open is given by:

$$E(x) = E_1(x) + E_2(x) \tag{4}$$

We have thus that $I(x)$ is proportional to $|E_1(x) + E_2(x)|^2 = |E_1(x)|^2 + |E_2(x)|^2 + Re(E_1(x)E_2(x)^*)$, where $Re(E_1(x)E_2(x)^*)$ is the real part of the complex number $E_1(x)E_2(x)^*$. Since $I_1(x)$ is proportional to $|E_1(x)|^2$ and $I_2(x)$ is proportional to $|E_2(x)|^2$, this explains why $I(x) \neq I_1(x) + I_2(x)$, the difference exactly being proportional to the interference term $Re(E_1(x)E_2(x)^*)$. Hence the wave theory of light explains the appearance of interference. It predicts that if one diminishes the intensity of the source, it will just diminish the intensity of the final pattern, but not change its form. Interference remains present. But a pure wave description can also not account for all the experimental results that one obtained even in this double slit experiment. Indeed, if one exposes the photographic plate for a very short time, such that only a few photons can be absorbed, one sees that each photon produces a very localized impact on the plate and not a weak interference pattern. This also means that the wave picture does not explain all aspects of this experiment.

What seems to happen is the following: while the photons, as particles, arrive one after the other on the plate, their localized impact is distributed randomly over the plate, and it is only when a large number of photons have arrived at the plate that the overall distribution appears as an interference pattern. Because of this, we have no means to trace back through which slit a particle passed. It is as if each particle passed through both slits.

The behavior of light and electromagnetic radiation in general cannot be accounted by either with a wave description alone nor with a particle description alone. The term that was introduced by physicists to describe this conclusion is 'wave-particle-duality'. We have to mention that the double slit experiment was performed with electrons as well by Davisson and Germer in 1927.

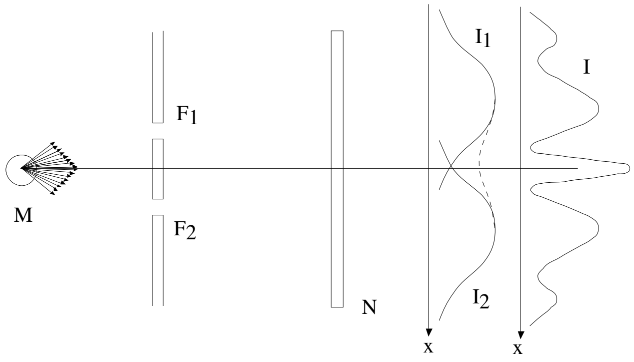

Fig 1: Illustration of the double-slit experiment. A monochromatic light source emits photons that pass through a two-slit screen and are detected on a photographic plate placed behind the screen. The sum $I_1(x)+I_2(x)$ of the intensities $I_1(x)$, when slit $F_2$ is closed, and $I_2(x)$ when slit $F_1$ is closed, is not equal to the intensity $I(x)$ measured when both slits are open.

# 5 Wave and particle or neither wave nor particle?

The two propositions that we can consider in relation with the paradoxical situation are the following:

**Proposition A:** *Light is a wave.*

**Proposition B**: *Light is a collection of particles.*

And let us now analyse the three attitudes that have appeared in the history of this problem.

## 5.1 The regularising attitude

The regularising attitude was predominant in the beginning years of quantum mechanics. At that time, the majority of physicists tried to 'resolve' the paradoxical aspects of quantum mechanics. The only two exceptions to this attitude were perhaps Heisenberg, who showed from the beginning a strong resistance against trying to explain the new quantum mechanics by means of classical ideas, and Dirac, who found that the mathematical formalism - even containing paradoxical aspects when interpreted - had to come first.

The most clear and explicit attempt to eliminate the problem of the wave-particle duality is perhaps that of Erwin Schödinger. He wanted to reduce quantum mechanics to a 'classical wave mechanics', where the particle behaviour would appear as wave singularities. In Schrödinger's view the ontologic nature of the quantum entity is that of a wave. The approach of Schrödinger could count on much sympathy of many physicists of that time among whom also Albert Einstein.

Because he was searching for a wave mechanics, Schrödinger first derived an equation of motion of the second degree, in analogy with classical wave equations. This equation however did not solve the problems that Schrödinger was investigating and by purely mathematical intuition he stepped over to a first degree equation of motion - now called the Schrödinger equation - having to introduce explicitly a 'complex' coefficient in the equation[3].

Schrödinger's regularising attempt failed because the manifest particle behavior, certainly after the well documented Compton effect, could not be explained in a satisfactory way.

Parallel to Schrödinger's attempt for a complete wave picture, Niels Bohr developed what is now commonly called the Copenhagen interpretation. Also the Copenhagen interpretation is an attempt to regularise the paradoxical situation. It is inspired by the fact that the wave behavior of the quantum entity

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[3] The second degree equation that Schrödinger proposed was introduced later again by Klein and Gordon in quantum field theory and is now called the Klein-Gordon equation.

shows itself only under well defined experimental situations - typically interference experiments - and also the particle behavior of the quantum entity shows itself only under well defined experimental situations - e.g. detection experiments. Hence Bohr proposed that the nature of the quantum entity - wave or particle - would be determined by the experimental setup [4], and he called this the 'principle of complementarity'.

Bohr states explicitly that neither proposition A nor proposition B make sense if one does not specify the detailed experimental setup. Hence Bohr believes that the behavior of light is wave-like or particle-like, but the wave-like nature manifests under a particular experimental setup while the particle like nature manifests under another particular experimental setup. According to Bohr, light 'is' never simultaneously a wave and a collection of particles, hence there is no contradiction. The propositions A and B do not make sense apart from the experimental setup, and according to Bohr, they should be rephrased as follows:

**Proposition A (Bohr):** *Light manifests as a wave using experimental setup C*

**Proposition B (Bohr):** *Light manifests as a collection of particles using experimental setup D*

Bohr's proposal indeed resolves the inconsistency, and although the complementarity principle is generally accepted as a solution to the paradoxes of quantum mechanics by the majority of physicists, those who work on the *foundations* of quantum mechanics are not satisfied with it. Indeed, the complementarity hypothesis introduces a fundamental subjectivistic element in the nature of the quantum reality. This has been most dramatically exposed in the delayed choice experiments proposed by Archibald Wheeler, which have been performed in the laboratory.

In a delayed-choice experiment, the experimental setup that, following the Copenhagen interpretation, gives meaning to propositions A and B, is made only after the light has been emitted by the source. This experiment shows us that a choice made in the present can influence the past. Wheeler's reasoning is based on an experimental apparatus as shown in Figure 2, where a source emits extremely low intensity photons, one at a time, with a long time interval between one photon and the next. The light beam is incident on a semi-transparent mirror $A$ and divides into two beams, a northern beam $n$ and a southern beam $s$. The beam $n$ is again reflected by the totally reflecting mirror $N$ and sent towards the photomultiplier $D_1$. The beam $s$ is again reflected by the totally reflecting mirror $S$, and sent towards the photomultiplier $D_2$. We know that the outcome of the experiment will be that every photon will be detected either

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[4] What actually is meant when we talk about the 'experimental setup', is the 'interplay' between the specific measurement apparatus and the entity under consideration

by $D_1$ or by $D_2$. Following the Copenhagen complementarity interpretation, this experimental situation pushes the photons to 'be' particles, which will be detected either in the northern detector $D_2$ or the southern detector $D_1$. It is rather easy to introduce an additional element in the experimental setup that, following the Copenhagen interpretation, pushes the photons to 'be' a wave. Wheeler proposes the following. We introduce a second semi-transparent mirror $B$ as shown on Figure 3, and the thickness of $B$ is calculated as a function of the wavelength of the light, such that the superposition of the northern beam and the southern beam generates a wave of zero intensity.

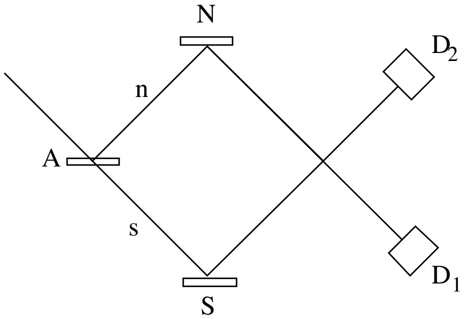

Fig. 2 : The delayed-choice experimental setup as proposed by John Archibald Wheeler. A source emits extremely low intensity photons that are incident on a semi-transparent mirror $A$. The beam divides into two, a northern beam $n$, which is again reflected by the totally reflecting mirror $N$ and sent towards the photomultiplier $D_1$, and a southern beam $s$, which is reflected by the totally reflecting mirror $S$, and sent towards the photomultiplier $D_2$.

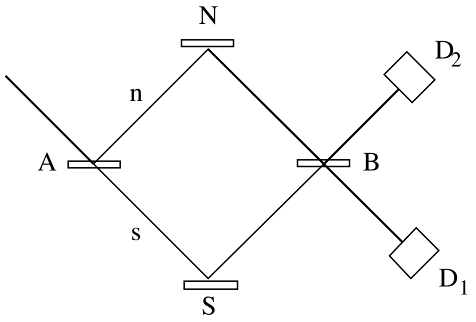

Fig. 3 : The delayed-choice experimental setup as proposed by John Archibald Wheeler, where a second semi-transparent mirror is introduced. Following the Copenhagen interpretation, in this experimental situation, the photons behave like a wave.

This means that nothing is detected in $D_2$, and all the light goes to $D_1$. This experimental setup pushes the photons of the beam into being completely wave-like: indeed, each photon interferes with itself in region $B$ such that it is detected with certainty in $D_1$. So, we have two experimental setups, the one shown in Figure 2 and the one shown in Figure 3, that only differ by the insertion of a semi-transparent mirror $B$. Wheeler proposed that the semi-transparent mirror $B$ be inserted or excluded at the last moment, when the photon has already left the source and interacted with the mirror $N$. Following the Copenhagen interpretation and Wheeler's experimental proposal, the wave nature or particle nature of a quantum entity in the past could be determined by an experimental choice made in the present. We are dealing here with an inversion of the cause-effect relationship, that gives rise to a total upset of the temporal order of phenomena.

To indicate more drastically the profoundly subjective nature of the world view that follows from a consistent application of the Copenhagen interpretation, Wheeler proposes an astronomical version of his delayed-choice experiment. He considers the observation on earth of the light coming from a distant star. The light reaches the earth by two paths due to the presence of a gravitational lens, formed by a very massive galaxy between the earth and the distant star. Wheeler observes that one may apply the scheme of Figure 2 and 3, where instead of the semi-transparent mirror $A$ there is now the gravitational lens. The distant star may be billions of light years away, and by insertion or not of the semi-transparent mirror, we can force the next photon that arrives to have traveled towards the earth as either a wave or a particle. This means according to Wheeler that we can influence the past even on time scales comparable to the age of the universe.

Not all physicist believing in the correctness of the Copenhagen interpretation will go as far as Wheeler proposes. However the general conclusion of Wheeler's example remains valid. The Copenhagen interpretation makes it quite impossible to avoid such an fundamental acausal element in the nature of the reality of the micro world. We mention that this is the reason why many physicists have always been a bit skeptical towards Bohr's complementarity solution of the quantum paradoxes.

The third attempt at a regularising interpretation was originally proposed by Louis de Broglie in 1926 (de Broglie 1926) and taken up again many years later by David Bohm and Jean Pierre Vigier (Bohm and Vigier 1954). It involves the idea of representing the quantum entity by a wave and a particle. The particle has the properties of a small projectile, but is 'accompanied' by a wave which is responsible for the interference patterns[5]. Actually, this wave is only detectable through it's influence on the particle by means of the quantum potential, and in no other way. The representation attempts to change as little as possible at the level of the underlying reality - the three-dimensional Euclidean space - where the quantum entities exist and interact. The quantum potential is effective in this three dimensional Euclidean space and is responsible for the specific quantum effects such as non-locality. This effect will be analysed in the next sections. We will not go into much of the details of the De Broglie-Bohm theory, but we mention that nowadays one knows that there is a deep structural failure in the theory. It is impossible to define the de Broglie-Bohm theory in three-dimensional space, because of the problems that arise when one tries to describe more than one quantum entity. In the case of an entity consisting of two quantum entities, the de Broglie-Bohm waves are waves in the six dimensional configuration space instead of the three-dimensional real space, and also the quantum potential acts in this six dimensional space. This means that the original goal, of real mechanics within three dimensional space, fails.

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[5] Because of the fact that wave and particle form together one quantum entity in this case, and there is no possibility of viewing the whole entity as a wave 'or' particle, we decided to call also this De Broglie-Bohm approach an example of the reguralising attitude.

Let us now investigate the paraconsistent attitude to handle inconsistencies.

## 5.2 The paraconsistent attitude

Most working experimenters and experimentally oriented theoreticians adopt this paraconsistent attitude. They allow quantum entities to be waves 'and' particles at once, and they know how to deal in a subtle way with this inconsistency. They use the familiar pictures of waves or particles and just work with both pictures. They set up new experiments to analyse specific questions and it seems to be a fruitful approach for the creative work of the experimenter. Since the paraconsistent attitude is a pragmatic attitude in relation to the quantum paradoxes, it has not been subject of extensive theoretical or philosophical analysis. We will find it exposed, perhaps unconsciously, in many textbooks on quantum mechanics. To show this, the best we can do is refer explicitly and in a literal way to what is written in one of these textbooks, namely 'Mécanique Quantique' of Claude Cohen-Tanouji, Bernard Diu and Franck Laloë (Cohen-Tanouji 1973), a textbook that is used in many European Universities. The authors are quantum opticians, and after a detailed analysis of the double slit experiment, they conclude: *Les aspects corpusculaire et ondulatoire de la lumière sont inséparables; la lumière se comporte à la fois comme une onde et comme un flux de particules, l'onde permettant de calculer la probabilité pour qu'un corpuscule se manifeste*[6]*.* So for many experimenters and experimentally oriented theoreticians, proposition A and proposition B are true at once.

## 5.3 The paracomplete attitude

A paracomplete attitude is characterized by the fact that both proposition A and proposition B are considered to be false. Quantum entities are neither waves, nor particles, but something completely different. This completely different 'thing' has some wave aspects and also some particle aspects, but it cannot be reduced to one of them (regularising attitude), and also cannot be reduced to both of them at once (paraconsistent attitude). As a consequence the considered 'wave-particle duality' interpretation is incomplete. Many theoretical physicists working on the foundations of physics adopt this attitude. Since in this case the existing 'wave-particle duality' attempts to describe quantum reality are abandoned, it is difficult to say what will be substituted for it. This means that the main difficulty with a paraconsistent attitude is the search for new intuitive pictures that can substitute for the wave-particle pictures. In Brussels, some of our research group on the Foundations of Quantum Mechanics elaborate an interpretation that falls within this attitude, and we will shortly expose it as an example.

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[6] Our english translation: The wave-like aspects and particle-like aspects of light are inseparable; light behaves at the same time as a wave and as a collection of particles, and the wave permits to calculate the probability that a particle manifests itself.

The interpretation that we are elaborating has been called the 'creation discovery view'. We refer to (Aerts 1992, 1999) for a detailed exposition of the 'creation discovery view' itself, and to (Aerts 1983, 1986, 1990, 1995, Aerts, Coecke and Smets 1999) for different aspects of this 'creation discovery view'. Here we will give only a short description of it. Quantum entities are considered neither waves nor particles, but real entities of a yet unknown nature, and what is essential is that they can be in states such that they are not localized - meaning that they are not present inside space. In this view localisation means that we pull the quantum entity inside space, and there it manifests itself as if it were a particle. Before the detection experiment that makes the localisation happen has been carried out, the quantum entity is generally not inside space. The act of pulling the particle into space 'creates' in part the position of the particle.

Let us explain shortly how the 'creation discovery view' is different from both of the above-mentioned interpretations, the de Broglie-Bohm interpretation and the Copenhagen interpretation. It is a realist interpretation of quantum theory in the sense that it considers the quantum entity as existing in the outside world, independent of us observing it, and with an existence and behavior that is also independent of the kind of observation to be made. In this sense it is strictly different from the Copenhagen interpretation, where the mere concept of a quantum entity existing independently of a measurement process is declared to be meaningless. The creation-discovery view however is not like the de Broglie-Bohm theory, which views quantum entities as point particles moving and changing in our three-dimensional Euclidean space, and where detection is considered to be just an observation that does not change the state of the quantum entity. In the creation-discovery view it is taken for granted that measurements, in general, *do change the state of the entity* under consideration. In this way the view incorporates two aspects, an aspect of 'discovery' referring to the properties that the entity already had before the measurement started (this aspect is independent of the measurement being made), and an aspect of 'creation', referring to the new properties that are created during the act of measurement (this aspect depends on the measurement being made).

The crucial point is that this dual aspect of the measurement - creation and discovery - is also present in a detection measurement. Intuitively, we associate the detection process with the determination of a spatial position which already exists. But now, we must learn to accept that the detection of a quantum entity involves, at least partially, the creation of the position of the particle during the detection process. The act of finding or not finding a quantum entity in a given region takes place only after setting up the measuring apparatus used for detection, and it requires the interaction of the quantum entity with that measuring apparatus.

Clearly the creation discovery view makes it necessary to reconsider our concept of space. If a quantum entity in a superposition state between two separate regions of space is only potentially present in both of these region, then space is no longer the setting for the whole of physical reality. Space, as we intuitively understand it, is in fact a structure within which classical relations between macroscopic physical entities are established. These macroscopic entities are always present in space, because space is essentially the structure in which we situate these entities. This need not be, and is not the case for quantum entities. In its normal state, a quantum entity does not exist in space. It is only by means of a detection experiment that it is, as it were, pulled into space.

Let us consider a delayed choice experiment, and describe this situation within the creation discovery view. We accept that the photon while it travels between the source and the detector is not inside space. It remains one entity traveling through reality (not space-time) and the two paths $n$ and $s$ are regions of space where the photon can be detected more easily than in other regions of space when a detection experiment is carried out. The detection experiment is considered to explicitly contain a creation element, and it pulls the photon inside space. If no detection experiment is carried out the photon is not traveling on one of the two paths $n$ or $s$.

We now can understand how the 'subjective' part of the Copenhagen interpretation disappears. In the creation discovery view, the choice of the measurement, whether we choose to detect or to conduct an interference experiment, does not influence the intrinsic nature of the quantum entity. In both cases the quantum entity is traveling outside space, and the effect of an experiment becomes apparent only when the measurement begins. If a detection measurement is chosen the quantum entity starts to get pulled into a place in space where it localizes. If an interference experiment is chosen the quantum entity remains outside space, not localized, and interacts from there with the macroscopic material apparatuses and the fields, and this interaction gives rise to the interference pattern.

## 6 The strange effect of non-locality

In this section we put forward one of the experiments on single quantum entities that illustrates, in our opinion, the problem of non-locality as encountered in quantum mechanics in its most crucial form. It is an experiment with neutrons in a neutron interferometer performed by Helmut Rauch and his collaborators. The preparation of the experiment is published in (Rauch et al. 1974), while the actual experiment, the one we present here, was performed a year later and the results were published in (Rauch et al. 1975). Helmut Rauch wrote a review article about the multiple neutron experiments that have been performed (Rauch 1988).

Helmut Rauch and his group built their first neutron interferometer in 1976. Starting from a perfect monocrystalline silicium block, they cut out a crystal in the shape shown in Figure 4, with three parallel walls or lips of precisely the same thickness. In their experiments, they directed a neutron beam onto one side of the crystal lips, and detected it on the other side. According to quantum mechanics, the beam should behave in a rather mysterious manner, and Rauch and his group wanted to verify if the predicted behavior was correct.

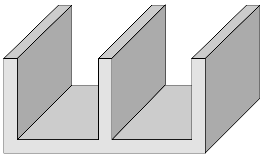
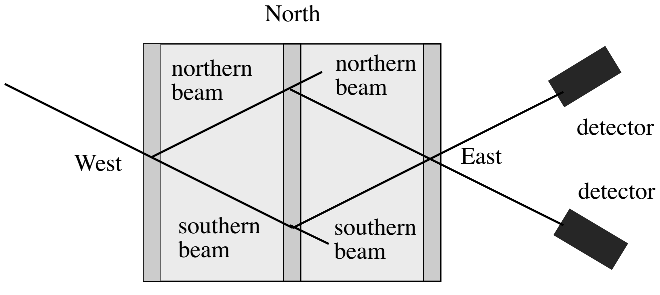


Fig. 4: The perfect silicium crystal, as used by Helmut Rauch's group at the Laue-Langevin Institute in Grenoble.

The beam was directed onto the crystal from the "northwest" direction (see Figure 5). On the first lip, the incident beam splits into two beams, which we shall call the northern and the southern beams. These then travel on towards the second lip. The northern beam undergoes refraction at the first lip, and travels on a northeast course, while the southern beam continues in the prolongation of the incident beam. On the second lip, the two beams again split, and of the four resultant beams, two converge from north and south to cross on the third lip. Two detectors placed on their paths make it possible to count the neutrons as they emerge from the crystal. Rauch's crystal is 7 cm long and 5 cm wide, so that the top view of Figure 5 is half of the real size. The neutrons are emitted one at the time from a reactor at an average speed of 2200 meters per second (approximately 5000 miles per hour) and on average are separated by a distance of 300 meters. This means that there will never be more than a single neutron within the crystal. In point of fact, when a given neutron passes through the crystal lips, the neutron that follows has not yet been produced in the reactor.



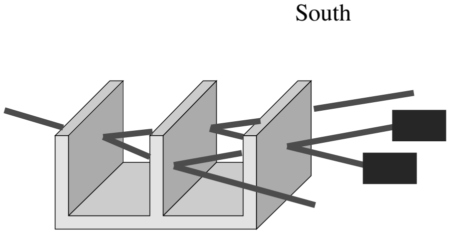


Fig. 5: Two representations of the Rauch experiment. The incident beam comes in from northwest, and is split on the first lip into two beams: one is refracted to the northeast (the northern beam), and the other (the southern beam) continues in the southeasterly direction. On the second lip there is a further splitting giving rise to four beams, of which two, the northern and the southern beam, cross on the third lip, and upon emerging from the crystal, are detected, and the neutrons counted.

In Rauch's experiments, each of the neutrons has a "coherence length" of one millionth of a centimeter. This means that the region within which the neutrons can act (or inversely, within which they can be acted upon) is restricted to a cube of sides one millionth of a centimeter. This is a very small volume indeed, and one of the problems that we are confronted with is that we lose all intuitive feeling on such small scales. To fully understand just how strange the results of Rauch's experiments are, let me scale the volume up to a size where we can better visualize it. Let us therefore reconsider the Rauch experiments on a scale 25 million times larger.

To do this, first take the real crystal and place it on a map of Europe scaled down twenty five million times. Then scale back up to get an imaginary super crystal covering a large area of Central Europe (Figure 6). The neutrons will now seem to be coming in from over the Atlantic Ocean, penetrating the super-crystal in Paris. The first lip, in which the neutron beam is split, lies over France and Great Britain. The northern beam flicks north-east over Belgium, and penetrates the second lip somewhere between Denmark and Norway. The southern beam passes over Bern, and reaches the second lip in Trieste. In the second lip, the beams are again split in two, so that four beams emerge, of which two intersect in Warsaw. The northern beam has passed over Copenhagen, and the southern over Vienna. Upon emerging from the crystal, the neutrons fly on towards Saint Petersburg or the Crimea, where they will be detected.

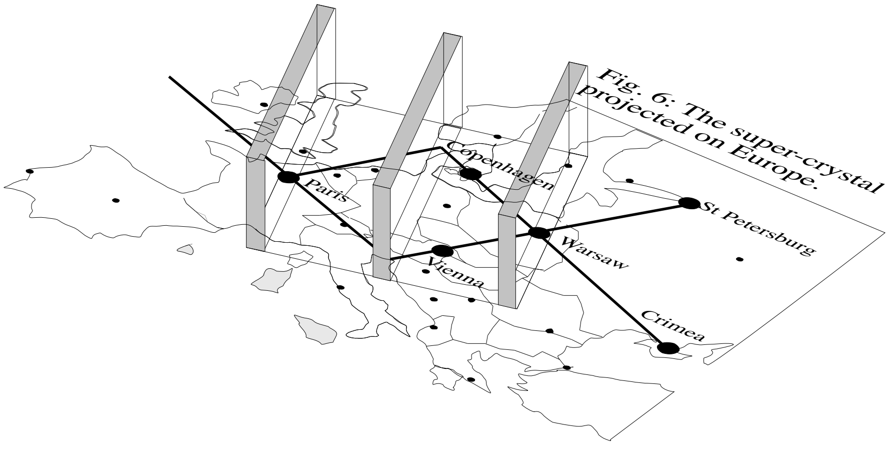


Fig. 6: The super-crystal projected on Europe.

We mentioned that in the real experiments the neutron field of influence can be considered as localized within a small cube of side one millionth of a centimeter. This becomes a cube of 25 centimeters on the scale for which the crystal covers half of Europe.

The passage of the neutron beam through the crystal lips will probably have suggested the following picture in most readers' minds: the neutrons as small projectiles, and the beam as a machine-gun fire of these projectiles. Let us think through a Rauch experiment assuming that the projectile analogy is correct. The machine-gun which is firing the neutrons lies somewhere over the Atlantic Ocean and is aiming at Paris. Remember that there is never more that a single neutron within the crystal at any given moment. This means that our machine-gun fires very slowly, one neutron after the other at large time intervals. A given neutron will have been detected in Saint Petersburg or in the Crimea long before the next neutron is fired. In our projectile analogy we can thus consider individual trajectories for each neutron taken separately. A given neutron comes in above the Channel, penetrates the crystal in Paris, and then either continues through towards Vienna on the southern beam line, or is deflected towards Copenhagen on the northern beam. In the second lip, the same thing happens again: either the neutron passes through undeflected and leaves the crystal, or it is deflected, and flicks over Vienna or Copenhagen in the direction of Warsaw where it reaches the third lip. Yet again the neutron can proceed undeflected, and it will finally reach the detectors in Saint Petersburg or the Crimea.

If this machine-gun projectile analogy were correct, it would be difficult to imagine anything mysterious about this experiment. But it is not correct. Let us just consider what actually happens in Rauch's experiments.

> *The experimental setup is such that Rauch is able to act upon each neutron as it crosses lip 2 of the crystal, i.e. in our upscaled model, within a 25 centimeter cube either in Copenhagen, or in Vienna. More precisely, Rauch can rotate the neutron, using experimental apparatus located in Copenhagen or Vienna, and which has only a local effective range. The rotation of the neutron can be carried out from either of the two experimental sites, Vienna or Copenhagen, and independently from through which city the neutron has passed, it will be observed by one of the detectors, in St.Petersburg or in the Crimea.*

From this it is clear that the neutron does not behave like a small projectile, for then it would pass either through Copenhagen, and Rauch could not rotate it from Vienna, or it would pass through Vienna, so that he could not act on it from Copenhagen. The experiment establishes that it is truly possible to rotate the neutron both from Copenhagen and from Vienna, without anything happening in the space between Vienna and Copenhagen. No signal which could influence the neutron in any way is transmitted between Vienna and Copenhagen.

The apparatus that Rauch uses to rotate the neutron is a magnetic field localized in a small region in Vienna and Copenhagen. There is no possibility whatsoever that the magnetic field used in Copenhagen to rotate the neutron could have any action outside Copenhagen, let alone in Vienna, at least if we think of magnetic forces varying in space. And there is no possibility that the neutron is partly in Copenhagen and partly in Vienna (whatever this would mean), because, if we were to set up detectors there, what we would detect would always be either a complete neutron or no neutron. More specifically, there is one chance out of two for the whole neutron to be detected in Copenhagen and one chance out of two for it to be detected in Vienna. It is 'as if' the single neutron is simultaneously present in both places, in the small cube in Vienna and in the small cube in Copenhagen, and that it can be acted upon from both these places as though it really and truly were there. An object which is simultaneously present in two distant places - can such a thing possibly exist?

## 7 The three attitudes and non-locality

We have given a full description of Rauch's experiment and the strange effect of non-locality that occurs from an experimenter's point of view. Our conclusion about the experimental facts in relation to non-locality is the following: an entity in a non-local state is such that it 'can be' detected or manipulated within distant separated regions of space, without that it essentially 'is' in one of these regions, the connotation 'is' being used here now in the normal classical way. Let us see whether we can again put forward two propositions in relation to this non-locality effect.

**Proposition A:** *The quantum entity is in Copenhagen*[7]*.*

**Proposition B:** *The quantum entity is in Vienna.*

Let us now turn back to the three attitudes and see how the physicist tried to handle non-locality.

### 7.1 The regularising attitude

In relation to non-locality we have to mention that there is still a small group of physicists who criticise the experiments themselves, and try to find loopholes in the experimental setups. Their attempts are of course classified within the regularising attitude. We will not go into details about these criticisms, because they are of a very technical nature. The majority of physicists as well as those working on the foundations of quantum mechanics, have now however accepted the non-locality effect as a genuine quantum mechanical effect. Since the specific non-locality effect, as demonstrated in Rauch's experiment, is much more recent than the wave-particle duality effect, it has been considered in much less detail than the previously mentioned theories developed according to the regularising attitude, the Bohr complementarity interpretation and the de Broglie-Bohm interpretation. Both interpretations, however, resolve the paradoxical situation

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[7] Although the places Copenhagen and Vienna have only been introduced for the upscaled model of the Rauch experiment, we will use them without giving rise to confusion in our logical analysis as well.

by stating that proposition A and proposition B are not true at once. Hence the neutron is either in Copenhagen, or it is in Vienna, but not in the two places at once.

Within the Copenhagen interpretation it will be pointed out that the non-locality effect is only observed when the experimental setup is such that the neutron 'is' a wave and hence, indeed a wave that is present in the two places, Copenhagen and Vienna. The particle nature only manifests itself within another experimental setup, for example one that tries to detect the neutron in Copenhagen or in Vienna. This second experimental setup makes the neutron 'be' a particle, and as a consequence it is only at one place, Copenhagen or Vienna.

Within the de Broglie-Bohm theory, the particle is always only in one of the places, Copenhagen or Vienna, while the guiding wave is in the two places at once.

## 7.2 The paraconsistent attitude

As we already stressed in our analysis of the wave-particle duality, mostly experimenters will adopt the paraconsistent attitude. They will pragmatically reason about the situation as if the neutron is at the two places, Copenhagen and Vienna, at once. Hence proposition A and proposition B are treated as both true propositions for many experimenters. There exists also a well-known interpretation, the Feynman path integral version of quantum mechanics, where it is even theoretically stated that the neutron moves on two paths at once. We refer to (Feynman 1985) for a detailed exposition of this interpretation.

## 7.3 The paracomplete attitude

Many theoreticians adopt the paracomplete attitude. The quantum entity is considered to be at neither of the two locations. It is through those theoreticians that we inherited the label 'non-local' for this effect by which we mean a specific space-related manifestation of a quantum entity. In the Brussel's 'creation discovery view' this specific space-related manifestation of a quantum entity is made explicit and interpreted as a 'real' and 'genuine' non-spatial state for a quantum entity, meaning that the entity can be literally out of space. It is explicitly accepted that the hypothesis that every entity at every moment is present in space cannot be retained in quantum mechanics. The behaviour of quantum entities observed in e.g. Rauch's experiment, is interpreted as a direct manifestation of this non-spatial state, and shows that the idea of an all-embracing space must be incorrect (Aerts 1983, 1986, 1990, 1992, 1995, 1999, Aerts, Coecke and Smets 1999). As mentioned already, within the *creation discovery view* it is taken for granted that during an act of measurement there are always two aspects, a *discovery* of a part of reality that was present independently of whether the act of measurement would have been carried out, and a *creation* that adds new elements of reality to the process of measurement and the entity under investigation. More precisely, when we come back to the situation of Rauch's experiment, it is the hypothesis that all of reality be contained within space that turns out to be at stake here. Indeed, within *'the creation discovery view'* applied to the micro-world, the creation aspect of a quantum measurement of detection of a quantum entity contains partly the creation of the *location* of the quantum entity itself. This means that the location of this quantum entity *did not* exist before the entity was detected, and this location is created during the process of detection. The same is true for the 'momentum' of a quantum entity. It is partly created during the process of measuring this property, and did not exist before. As a consequence, a quantum entity in most of its states does not have a location. In technical jargon they say that it is *not localised* and does not have a momentum. So, the mysterious aspects of Rauch's experiments are a consequence of the fact that the neutron involved is 'not present in space'. And that the two experimental cubes, the one in Copenhagen and the one in Vienna, can be considered as windows through which we can act on the neutron in its non-spatial state. The two cubes are openings which give us access 'out of space'. The classical concept of space has been given up; it is no longer an all-embracing setting in which the whole play of reality takes location, but a structure that engulfes only the macroscopic entities, that consist of a great number of 'almost' localized quantum entities.

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